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Neutron and gamma-ray measurements of the solar flare of 1991 June 9

James M. Ryan
University of New Hampshire, James.Ryan@unh.edu

D J. Forrest
University of New Hampshire - Main Campus

J Lockwood
University of New Hampshire - Main Campus

M Loomis
University of New Hampshire - Main Campus

Mark L. McConnell
University of New Hampshire - Main Campus, mark.mcconnell@unh.edu

See next page for additional authors

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Authors
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NEUTRON AND GAMMA-RAY MEASUREMENTS OF THE SOLAR FLARE OF 1991 JUNE 9

J. Ryan, D. Forrest, J. Lockwood, M. Loomis, M. McConnell, D. Morris,
W. Webber
Space Science Center, Morse Hall, University of New Hampshire,
Durham, NH 03824

K. Bennett, L. Hanlon, C. Winkler
Astrophysics Division, European Space Research and Technology Center, Noordwijk,
The Netherlands

H. Debrunner
Physikalisches Institut, University of Bern, 3012 Bern, Switzerland

G. Rank, V. Schönfelder
Max-Planck Institut für Extraterrestrische Physik, 8046 Garching, Germany

B.N. Swanenburg,
SRON-Leiden, 2300 RA Leiden, The Netherlands

ABSTRACT

The COMPTEL Imaging Compton Telescope on-board the Compton Gamma Ray Observatory measured significant neutron and γ-ray fluxes from the solar flare of 9 June 1991. The γ-ray flux had an integrated intensity (> 1 MeV) of ~30 cm^{-2}, extending in time from 0136 UT to 0143 UT, while the time of energetic neutron emission extended approximately 10 minutes longer, indicating either extended proton acceleration to high energies or trapping and precipitation of energetic protons. The production of neutrons without accompanying γ-rays in the proper proportion indicates a significant hardening of the precipitating proton spectrum through either the trapping or extended acceleration process.

INTRODUCTION

Active Region 6659 produced powerful flares throughout its transit across the disk from 2 June 1991 to 16 June 1991. On 9 June the region produced an X10/3B class flare that was observed by all instruments on the Compton Gamma Ray Observatory. At this time the active region was located at N34E04 in heliographic coordinates. The flare was impulsive in nature, with a duration on the order of 8 minutes and exhibiting two intense spikes of γ-ray emission > 600 keV. The Sun was positioned approximately 15° off the telescope axis, well within the instrument field-of-view (FOV).COMPTEL measures γ-rays by two means. These are the "telescope" and "burst" modes. The two modes of operation are described elsewhere[1]. The "telescope" mode relies on the Compton scattering process, whereby the γ-ray Compton scatters in a D1 detector (liquid scintillator) and then scatters again in a separate D2 (NaI) detector. In measuring the solar γ-ray flux, the scattering angle, deduced from the Compton formula and the direction of the scattered γ-ray must be consistent with a solar origin for subsequent analysis. The "burst" mode utilizes two of the D2 detectors as omnidirectional spectrometers. Neutrons are only measured in the "telescope" mode, but here the Compton scatter is replaced by an elastic neutron-proton scatter in the organic liquid scintillator in the D1 detector. The energy estimate of the recoil neutron is performed by measuring the time-of-flight of the neutron from D1 to D2. The solar γ-ray and neutron measurement capabilities of the instrument are described in greater detail by Ryan *et al.* [2].

OBSERVATIONS

The raw omnidirectional count rates of individual detector types are shown in Figure 1. This X10/3B flare was impulsive in nature with a duration on the order of 8 minutes and exhibiting two intense spikes of γ-ray emission. The GOES X-ray flare started at 0134 UT peaking at 0143 UT. The γ-ray onset occurred at 0136 UT and the impulsive phase lasted until ~ 0142 UT. Satellite sunrise precedes the flare only by a few minutes, thereby allowing a long observation of any extended flare emissions, such as neutrons. The count rates in the D1 and D2 detecting systems with thresholds of ~ 60 and ~ 350 keV, respectively, show how the flare behaved in hard X-rays and γ-rays. The slow rise and fall of the D2 counts rate after the impulsive phase arises from excursions in geomagnetic latitude and is not related to the flare. Also shown is the count rate in the Anticoincidence detection system (threshold ~100 keV). These detectors reject charged cosmic ray particles but are also sensitive to large thermal X-ray fluxes. At the X10 level, the X-ray flux falling upon the large Anticoincidence detectors results in pulse pile-up and large dead time effects for the whole instrument. The Anticoincidence rate qualitatively traces the magnitude of the dead time effect, which reaches a value of approximately 75% during the impulsive phase. The dead time effect improves to the ~ 50% level by 0155 UT.

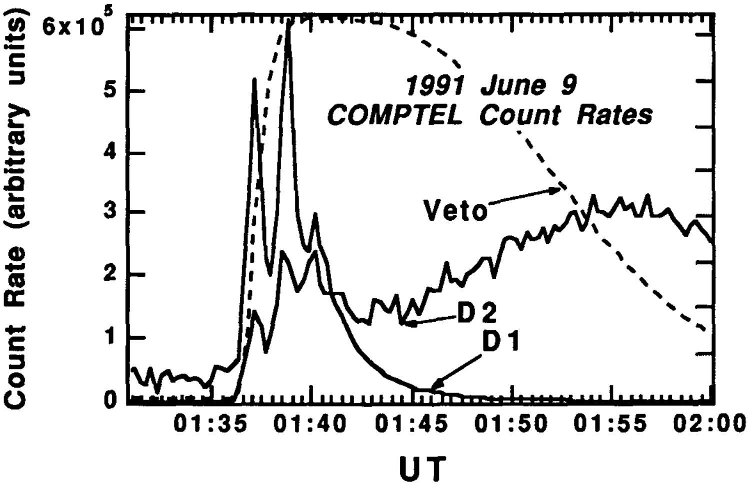

FIG. 1: Raw COMPTEL housekeeping data.

During the impulsive phase the γ-ray emission spectrum is obtained by selecting the telescope events consistent with the Sun's location, as shown in Figure 2. From the γ-ray events in the telescope mode, although not shown here, an image of the sun can be constructed[3]. The strong line from deuterium formation is seen at 2.2 MeV. Other lines are also present with less statistical significance. No background spectrum has been subtracted, but few photons are expected, since the background is suppressed by the large signal-to-noise ratio large.

Solar neutron events from 0155 UT to 0222 UT were selected from the data and reprocessed. This time selection avoids the troublesome period around the impulsive phase with large dead times and other instrumental effects. The time 0155 UT corresponds to a 50 MeV neutron produced at the flare start 0136 UT or a 60 MeV neutron from the flare maximum at 0139 UT. Some selection bias, therefore, exists for neutrons detected shortly after 0155 UT (real time). The selected data were subjected to similar geometric constraints as were the γ-rays, i.e., the origination direction of the neutron event must be consistent with the solar direction (± 10°). The scatter angle (ϕ) of the individual neutron events was restricted to 20° to improve the signal-to-noise ratio. The energy of each neutron is used to compute its production time at the Sun. Shown in Figure 3 in addition to the flux > 600 keV is the live time corrected and background subtracted intensity-time profile of the neutrons as produced at the Sun but plotted at the production time plus the light travel time over 1 AU (507 s). Therefore, photons and neutrons produced concurrently are plotted at the same time value even though the neutrons arrive later.

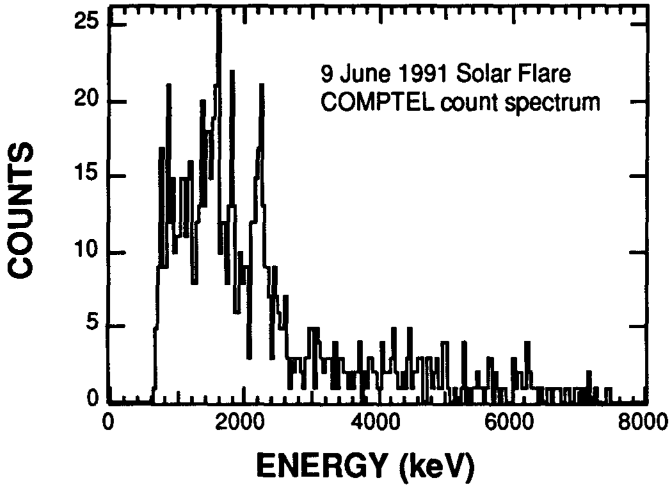

FIG. 2: The raw telescope mode count spectrum from the 9 June 1991 solar flare.

The background was estimated from the measured neutron flux ~ 24 hours later when the same orbital-geophysical conditions were reproduced. The on-board instrument software, however, was configured differently from the flare observation, being less restrictive in accepting neutron events. This resulted in a uniform 36%

increase in the neutron background count rate. The background rate was scaled downward by this factor in order to provide a representative background for the flare orbit on 9 June. The background corrections were successfully tested on similar background orbits to ensure that a null result is obtained. Identical data cuts then were made on both the flare data and the prescaled background data. Live time fractions of 60% to 100% were applied to the data as a function of real time from 0155 - 0220 UT.

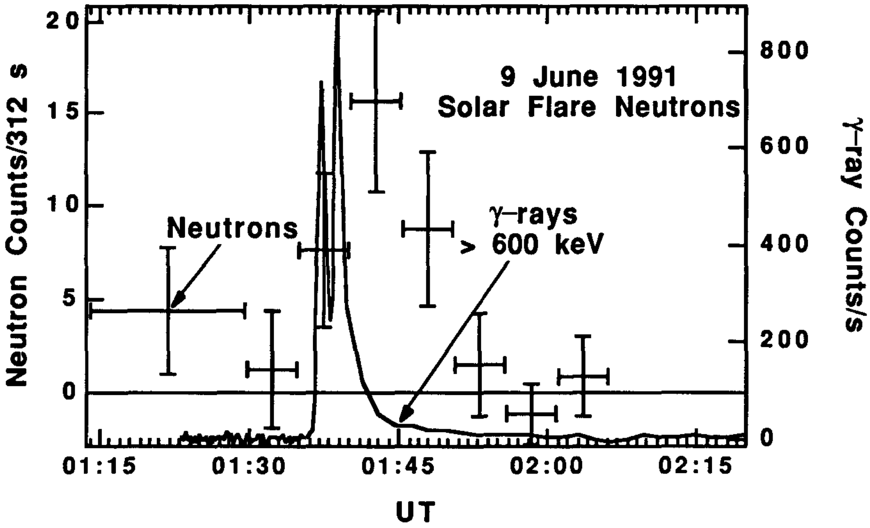

FIG. 3: Neutron and γ-ray emission-time profiles for the 9 June 1991 solar flare, plotted at the time corresponding to a photon arrival time.

DISCUSSION

The most important feature to note in Figure 3 is the time coincidence of the onsets of neutron and the γ-ray production. The neutron intensity-time profile is expected to be smoother and somewhat broader than that of γ-rays because of the neutron energy resolution which maps into an error (FWHM) in production time at the Sun (~ 1-3 minutes, dependent on energy). Although the γ-rays and neutrons are observed to start simultaneously, there is evidence that the neutron emission persists for ~ 10 minutes after the > 600 keV γ-ray flux has subsided.

This extended emission is evidence for a significant evolution (hardening) of the progenitor proton spectrum, arising from either additional acceleration or differential trapping and precipitation of protons. As seen in Figure 2 a large fraction of the γ-rays > 1 MeV are of nuclear origin. With no evolution of the proton spectrum, we would expect the > 600 keV γ-ray flux to follow the neutron production profile. However, a hardening of the spectrum would enhance the neutron emissivity with respect to that of the nuclear γ-rays. It should be noted, though, that the primary electron bremsstrahlung component has not yet been separated from the nuclear component, so that part of the decay of the flux > 600 keV could result from the decay of the pure electron component of the γ-ray flux.

The trapping scenario is consistent with the > 50 MeV γ-ray flux detected by EGRET after 0145 UT[4]. The net neutron count rate from 0136 UT to 0150 UT is positive at the 4.2 σ significance level. The absolute neutron flux is uncertain at this time due to the difficulty in computing the effective area of the instrument under the conditions of the flare and the data restriction used in the analysis. Work continues on this effort. The uncertainty of the instrument response manifests in the relative neutron flux among the three 5 minute intervals of neutron production. The assignment of a production time to an individual neutron is not affected by this uncertainty, only the intensity of the neutron emission. Thus, the intensity-time profile in Figure 3 may change shape when neutron fluxes are computed, but the duration of the event will remain unchanged.

In all other respects the 9 June 1991 was purely impulsive in nature, but the prolonged energetic particle activity as manifest in neutrons and γ-rays > 50 MeV establishes this flare as one of a class of *long duration* events, similar to that of 3 June 1982. Two models for describing this phenomenon have been put forth[5,6]. Ryan and Lee[5] propose that a steadily hardening proton spectrum is produced by proton trapping in a *turbulent* coronal magnetic loop with second order stochastic acceleration, while Mandzhavidze and Ramaty[6] posit that the protons responsible for extended high energy emission such as this arise in the impulsive phase with differential trapping and precipitation in a *relatively quiet* coronal loop. In either scenario, it is the diffusion of protons out of the loop which precipitate and produce the high energy emission. The data of the 9 June 1991 flare do not distinguish between the two models. With the great sensitivity of the instruments on the Compton Gamma Ray Observatory it is likely that other flares exhibiting this behavior will be observed or discovered in the data. By studying these flares we hope to gain a greater understanding of the processes of proton acceleration and transport in solar flares.

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